2005

On-farm evaluations of nitrogen management for corn production with precision farming technologies

Bradley Wilbert Van De Woestyne
Iowa State University

On-farm evaluations of nitrogen management for corn production with precision farming technologies

by

Bradley Wilbert Van De Woestyne

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Program of Study Committee
Alfred M. Blackmer, Major Professor
Paul F. Anderson
Richard M. Cruse
Thomas C. Kaspar
Kenneth J. Koehler

Iowa State University

Ames, Iowa

2005

UMI Number: 3172249

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Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Bradley Wilbert Van De Woestyne

has met the dissertation requirements of Iowa State University

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Major Professor

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For the Major Program

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank the following people and organizations that contributed in one way or another during my endeavors as a graduate student at Iowa State University.

First is Dr. Alfred M. Blackmer. Thank you for your guidance, incredible patience, and thoughtfulness toward me. I admire your ability to recognize the importance and meaning of our research, your ability to express those in written and spoken words, and the compassion you have for your work and the producers of Iowa.

Second is Dr. Tracy M. Blackmer. I appreciate your input for the papers and presentation we worked on and your knowledge and advice about topics too numerous to list.

Next are the professors willing to serve on my committee. They are Drs. Paul Anderson, Rick Cruse, Tom Kaspar, and Ken Koehler. Even though each has a busy schedule, they provided me with help and suggestions whenever I asked.

I would like to thank my fellow (current and past) colleagues in the research group. They are Peter Kyveryga, Dr. Jun Zhang, Natalia Rogovska, Gaylia Ostermierer, Mark Glady, Drs. Jason Ellsworth and Kipling Balkcom, the undergraduate employees who made my job easier, Ben Van Beek, Dustin Bollig, Eric Phipps, and Nate Hertel. I would like to especially thank Peter and wish him the best of luck.

I would like to thank all of the cooperating producers of the On-farm N Network. I especially thank Steve Fisher, Jay and Jerry Ostrander, Jim Andrew, Jim and Pat Juon, Jim Yoder, Steve Lawler, and Scott Chesnut.

The research was funded by the Iowa Soybean Association, John Deere, Dow AgroSciences, Agrium, and Terra.

Finally and most importantly, I would like to thank my family. Thanks for the support, encouragement, and motivation you've provided during my life. I would especially like to thank my father, who inspired me by simply being optimistic and hopeful.

CHAPTER I: GENERAL INTRODUCTION

Guidelines, or recommendations, for nitrogen (N) management in the Corn Belt are important to corn producers because fertilizer N must be applied for profitable corn production, because profit margins are narrow, and because N fertilization has been linked to local and regional water quality problems. Producers rely on these guidelines developed by Land-Grant Universities and government agencies because it is practically impossible for individuals to identify optimal rates, times, and methods of N fertilization. The guidelines have been developed by using data collected from small-plot experiments. Although the number of experiments was limited, the guidelines were based on the best information and knowledge available at the time.

Recent advances in technology lead to the development and use of precision farming technologies by crop producers in the Corn Belt. Examples of the technologies include yield-monitors on combines, global positioning systems (GPS), and geographic information systems (GIS). They enable producers to measure and record yields as combines move across fields and to organize and summarize these data. Many corn producers invested in these technologies to learn how to manage inputs like N. However, methods for using the new technologies to improve N management are only starting to be developed.

The technologies enable producers to measure yield responses to different N treatments, or management practices, on their fields. The producers can, therefore, evaluate alternative N management practices under conditions typically encountered in their fields. The producers can see the results firsthand. Although it is self evident that data can be collected across fields and at many sites, there are no established methods for organizing networks of producers to conduct on-farm trials and analyze all the results to refine guidelines for N management.

This dissertation describes efforts to develop methodology needed by organized groups of producers using the new technologies to evaluate and improve their management on their farms. The studies presented illustrate how two-treatment trials can easily be established and conducted by producers and how the results can be analyzed to evaluate and improve N management practices during corn production.

Dissertation Organization

The dissertation is organized into six chapters. The first is the general introduction to the dissertation. The next four chapters are manuscripts to be submitted for publication in relevant journals. The journals, in order of the chapters, are: Science, Journal of Soil and Water Conservation, Crop Management, and Agronomy Journal, respectively. The sixth and final chapter is a general conclusion.

CHAPTER II. REFINING ESTIMATES OF NITROGEN FERTILIZER NEEDS IN THE CORN BELT TO PROTECT WATER QUALITY

A paper to be submitted to Science

Bradley W. Van De Woestyne, Alfred M. Blackmer, and Tracy M. Blackmer

Abstract

New technologies were used to assess the on-farm impacts of reducing rates of nitrogen (N) fertilization for corn by approximately one-third. The results suggest that this reduction could be made without reducing profits for producers and that current guidelines call for more N than is needed when relatively efficient practices are used. Regional networks of crop producers using the new technologies offer a novel way to collect data needed to refine estimates of fertilizer needs and develop guidelines that should reduce hypoxia and other water quality problems linked to losses of N from agricultural soils.

Article

Nitrogen (N) that escapes from agricultural soils has long been recognized as a source of nitrate in local water supplies (*1, 2*). This N became recognized as a regional problem with the finding that hypoxia in large bodies of water such as the Gulf of Mexico may be linked to major agricultural regions such as the U.S. Corn Belt (*3, 4*). A goal of reducing the amounts of N carried to the Gulf of Mexico has been established (*5*), but it is not clear how this goal will be attained and what the cost will be. Although reducing rates of N fertilization is an obvious possible approach, this approach has not seemed practical because analyses (*6-9*) of impacts have assumed that the efficiency of N fertilization cannot be improved and that any reduction in rates of N fertilization will result in unacceptable reductions in profits for crop producers. This assumption is derived largely from modeled relationships between rates of N fertilizations and crop yields obtained in small-plot trials on research stations. There is reason to question this assumption because there is substantial disagreement among the models used to describe yield responses to fertilizer at near-optimal rates of N fertilization (*10*) (*11*). Moreover, measured economic optimum rates of N fertilization vary greatly with site conditions and with the specific fertilization practices used, so there seems to be opportunity to improve the efficiency of N fertilization by modifying practices.

We used recent advances often described as "precision farming technologies" to conduct many on-farm trials to assess the on-farm effects of reducing rates of N fertilization by approximately one-third (i.e., 56 kg N ha^{-1}) of those normally applied for corn grown after soybean (*12*). Because it was our intent to demonstrate the benefits of using relatively efficient fertilization practices, studies were restricted to sites where fertilizer N was applied no earlier than 2 weeks before planting. Each trial compared the producer's normal rate (mean of 169 kg N ha^{-1}) to the reduced rate in replicated strips at least 300 m long (*13*). The strips were 6 to 18 m wide and harvested by combines equipped with GPS, sensors that monitor flow of grain, and computers that record flows of grain as a function of location.

Mean yields of grain were 11.23 Mg ha^{-1} at the rates normally used by the producers and 10.97 Mg ha^{-1} at the reduced rate (Table 1). The mean decrease in yield (0.26 Mg ha^{-1}) had a 95% confidence interval of 0.19 to 0.35 Mg ha^{-1}. At normal prices for grain and fertilizer (*14*) the reduction in fertilizer costs (\$30.24 ha^{-1}) was slightly greater than the reduction in value of crop (\$21.80 ha^{-1}). The reduction of rates of fertilization would not have resulted in a significant reduction of mean profits for producers in this study.

The largest yield loss resulting from the reduction of fertilizer N was 1.91 Mg ha^{-1}, and yield reductions greater than 0.36 Mg ha^{-1} were observed at 18 of 76 sites. Although the higher rate of fertilization would have been profitable at these sites, these profits could not be obtained unless responsive sites could have been identified before the fertilizer was applied. Such responsive sites usually cannot be identified at this time, however, because responses to fertilizer are determined by many factors (i.e., weather, insects, diseases, etc.) that occur during the growing season. The problem of unavoidable uncertainty when estimating optimal rates of fertilization is widely recognized and usually addressed by recommending extra N, often called "insurance N", to avoid severe economic penalties associated with yield loss due to deficiencies of N (*15, 16*). The methods for estimating optimal rates of insurance N, however, usually are not described and have received little attention. Assessments of N fertilizer needs usually are based on too few observations to give reasonable estimates of uncertainty or risk for specific practices in specific farming systems and regions. It is likely that more insurance N is being applied than is optimal for producers.

Reducing rates of fertilization by 56 kg N ha^{-1} decreased the amounts of N harvested in grain by only 4 kg N ha^{-1}. A similar decrease in amount of N probably occurred in corn residues left in the field after harvest. The reduction in rates of fertilization, therefore, had the potential to reduce the amounts of residual nitrate in soils at the end of the season by up to 48 kg N ha^{-1}. Any reduction in amounts of residual nitrate is desirable because rainfall and transpiration patterns are such that water moving through soils is most likely to leach nitrate from soils between cropping seasons in this region (*17, 18*).

Reductions in residual nitrate should be expected to have no important effects on fertilizer needs for the next crop because fertilizer N is neither needed nor applied for soybean crops, which can obtain adequate N through symbiotic relationships with nitrogen-fixing microorganisms. Because soybean plants efficiently utilize any nitrate that is in soils (*19*), residual nitrate from one corn crop should be expected to have minimal effects on the fertilizer needs for the next corn crop. It is noteworthy that corn grown after soybean receives most of the fertilizer N applied in the Corn Belt.

Removal of 140 kg N ha^{-1} during grain harvest in fields where only 113 kg N ha^{-1} was applied should not be considered evidence that the lower rate resulted in an undesirable depletion of soil N or degradation of soil quality. It is well established that estimates of N fertilizer needs should be reduced when corn follows soybean rather than corn and that this reduction is necessary to account for the direct or indirect effects of soybean plants on supplies of plant-available N for the next crop (*20, 21*). This reduction is often described as a fertilizer-N "credit" from soybean and is often estimated to be about 45 kg ha^{-1}. Such credits illustrate the great importance of adjusting estimates of N fertilizer need to consider previous crops and other factors that are known at the time of fertilization.

The mean reduction in yields (0.26 Mg ha^{-1}, or 2.3%) observed in this study need not necessarily accompany a one-third reduction in mean rate of N fertilization in Iowa because many crop producers are currently using N fertilization practices that are much less efficient than studied here and because these producers should be expected to switch to more efficient practices in the future. Fertilizer N is often applied in the fall (about 6 months before plants begin rapid growth and uptake of N), for example, and losses of fertilizer N before plants grow often result in 20% loss of yield on years with above-normal amounts of spring rainfall (*22, 23*). Recent watershed-scale studies (*24*) have linked rainfall-induced losses of fertilizer N early in the season to high concentrations of nitrate in rivers and deficiencies of N in cornfields. Evidence for large losses of fertilizer N from soils to rivers before plants grow indicates that changes in fertilization practices could increase profits for producers while decreasing environmental degradation associated with the use of N fertilizers. We suggest that relatively inefficient fertilization practices are widely used today primarily because there have been no simple and effective ways for crop producers to compare the performance of alternative fertilization practices in their fields.

Fields receiving fall applications of fertilizer N were not included in our study because we reasoned that fertilizer needs should be estimated from data collected when relatively efficient fertilization practices are used. This approach is necessary to assess the costs and benefits of selecting a particular fertilization practice over another. This approach has not been emphasized in the past and current estimates of fertilizer need usually do not indicate the extent to which fertilizer needs vary with times and methods of fertilization commonly used within a region.

Estimates of fertilizer needs are formally expressed as "recommendations" or "guidelines" developed and promoted by government institutions and agencies. The most commonly used guidelines are based on an assumption that N fertilization rates should be proportional to the yield levels obtained within a given soil type or region. For much of the Corn Belt, N fertilizer needs are estimated by assuming that 21.4 kg N is needed per Mg of grain produced and that fertilizer needs should be reduced by subtracting credits for N supplied by other sources (*23*). Fertilizer needs for corn after soybean are estimated, therefore, by taking the difference between two estimates that have considerable uncertainty (i.e., fertilizer needs for corn grown after corn and the amounts of credit that should be given for N associated with soybean) rather than by direct methods as we demonstrate here. Ironically, it is not possible to identify the source or magnitude of possible errors in the commonly used guidelines by studying corn grown after soybean.

The commonly used guidelines should be questioned because only about 12.5 kg N is harvested in each Mg of grain, because the mean rate of fertilization normally used by the cooperating producers in our study was only 88% of that recommended, and because reducing this rate by one-third did not result in a loss of mean profits for the producers. Programs that promote the use of such guidelines should be considered a barrier to improving N management during corn production. This problem is noteworthy because government payments to producers are currently withheld unless producers follow existing guidelines and governments are developing rules that require crop producers to follow nutrient management guidelines (*25*).

A critical problem in refining estimates of fertilizer needs has long been the high cost of measuring yield responses to fertilizer N across the wide range of conditions found in production agriculture. This problem is exacerbated by rapid changes in the production practices most commonly used and increases in the numbers of alternative practices available with advances in technology. Important changes in production practices are occurring because yields are increasing at a mean rate of 0.12 Mg ha^{-1} $year^{-1}$ (Fig. 1). Increases in yield levels over the past 2 decades cannot be attributed to increases in N fertilization rates because mean rates of fertilization for the past 10 years (141 kg N ha^{-1}) are less than the mean rates (148 kg N ha^{-1}) during the preceding 10 years (*26*). This increase in yields should be attributed to changes in cultural practices that have increased the efficiency of N fertilization. New soil and plant tissue tests that help producers avoid unnecessary applications of N (*27*) undoubtedly have contributed to the increase in efficiency. Guidelines commonly given to producers do not reflect changes in efficiency that have occurred in the recent past or that should be expected in the future.

Our study demonstrates how organized networks of producers with precision farming technologies can rapidly and efficiently evaluate alternative management practices within a region or watershed and identify those which increase the efficiency of N fertilization and thereby increase profits for producers while reducing losses of fertilizer N to the environment. Publicly funded programs that encourage corn producers to continuously evaluate and improve their N fertilization practices offer a novel way to generate the data needed to continuously evaluate and refine guidelines for N management. This approach, however, requires considerable change in the methodology for estimating N fertilizer needs during crop production and developing nutrient management guidelines. This change is unlikely to occur unless the broader scientific community recognizes the limitations of currently used guidelines for N management, the new opportunity for improving these guidelines, and the potential benefits to society that are likely to result from such a change.

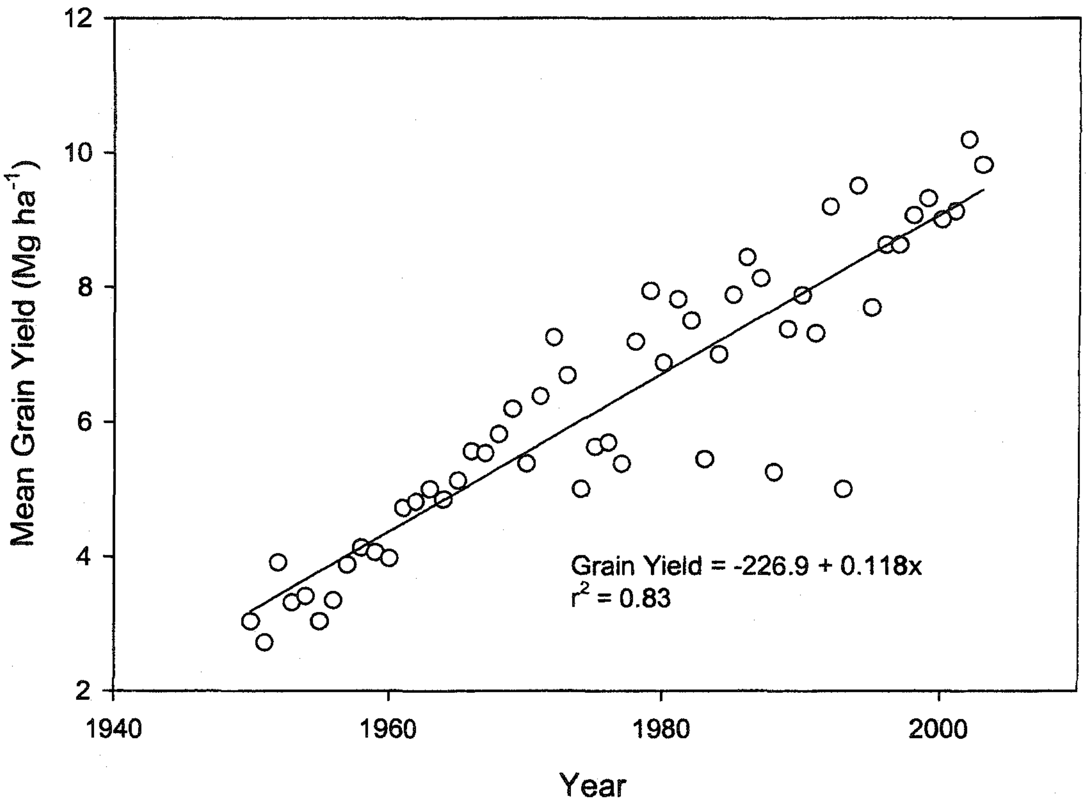

Figure 1. Trend for increasing corn grain yields in Iowa as reported by the National Agricultural Statistics Service (available online at http://www.usda.gov/nasss).

Table 1. Summary of rates of N fertilization and corn grain yields by site.

	Fertilizer N		Yield	
County (year)	Reduced Rate	Normal Rate	Reduced Rate	Normal Rate
	----- kg N ha^{-1} -----		----- Mg ha^{-1} -----	
Marshall[1] (02)	48	93	10.31	10.47
Linn (03)	56	112	11.14	10.89
Black Hawk (02)	67	123	11.78	12.10
Black Hawk (03)	67	123	9.06	9.39
Chickasaw (03)	75	142	9.95	10.23
Chickasaw (02)	75	142	9.15	9.56
Buchanan (01)	78	140	9.37	9.48
Tama (02)	84	140	12.11	12.42
Cerro Gordo (02)	84	140	12.02	12.13
Buena Vista (01)	84	140	10.24	10.43
Buchanan (02)	84	140	9.75	9.73
Delaware (01)	84	140	12.83	12.88
Story (02)	84	157	10.78	10.71
Grundy (02)	89	145	9.03	9.05
Black Hawk (01)	90	146	7.13	7.39
Grundy (02)	90	140	10.66	10.97
Grundy (01)	90	146	12.75	13.06
Chickasaw (01)	90	146	9.89	10.30
Palo Alto (03)	90	146	12.40	13.56
Palo Alto (02)	90	146	10.81	11.00
Howard (02)	95	140	8.47	8.59
Howard (02)	95	140	11.77	12.41
Chickasaw (01)	95	163	9.57	9.61
Buchanan (01)	96	152	10.92	11.19
Buchanan (01)	101	157	12.44	12.50
Bremer (01)	101	151	12.50	12.95
Palo Alto (01)	102	158	9.73	10.12
Hardin (02)	106	163	12.04	12.12
Hardin (02)	106	163	11.70	12.07
Hardin (02)	106	163	12.45	12.61
Clay (02)	112	224	12.07	12.19
Boone (01)	112	168	12.51	12.77
Boone (01)	112	168	10.86	11.05
Floyd (00)	112	168	10.58	10.80
Linn (03)	112	168	12.01	12.04
Polk (02)	112	168	11.05	11.15
Floyd (02)	112	168	10.09	10.16
Cerro Gordo (00)	112	168	9.91	9.68
Buchanan (00)	112	168	10.66	11.01
Howard (01)	112	146	9.71	9.96
Buchanan (00)	112	168	10.41	10.36
Franklin (01)	112	168	9.15	9.10
Bremer (01)	112	156	12.17	12.10
Black Hawk (01)	112	168	11.88	13.78
Washington[1] (01)	114	173	11.22	11.73
Buchanan (01)	118	174	12.42	12.74
Buchanan (01)	118	174	11.17	11.53
Black Hawk (02)	118	174	10.21	10.50
Chickasaw (01)	118	174	8.90	8.80
Buchanan (02)	119	175	13.56	14.09
Greene (01)	123	179	9.29	9.54
Floyd (01)	123	179	11.72	11.61
Bremer (02)	126	182	12.00	11.86
Bremer[1] (01)	129	185	9.59	10.14
Bremer[1] (01)	129	185	11.47	11.61
Washington[1] (02)	129	191	11.43	12.43
Washington[1] (02)	129	191	12.82	14.06
Black Hawk (01)	130	186	10.21	10.35
Chickasaw (02)	131	187	8.75	8.81
Cerro Gordo (01)	135	191	11.69	11.77
Story (01)	135	191	11.93	12.31
Delaware (01)	135	191	9.63	9.91
Story (03)	146	202	10.42	10.41
Story (03)	146	202	11.28	11.46
Franklin (00)	146	202	9.21	9.26
Chickasaw (01)	146	202	9.25	10.00
Buchanan (00)	146	202	14.17	14.33
Story (01)	146	202	11.43	11.49
Johnson (02)	146	202	11.41	13.02
Story (01)	151	207	10.63	10.78
Buchanan (00)	157	213	9.14	9.34
Story (02)	164	220	13.32	13.61
Story (02)	164	220	13.84	13.88
Story (02)	164	220	13.22	13.41
Grundy (01)	164	231	10.87	11.39
Buchanan (00)	168	224	11.35	11.44
Mean	113	169	10.97	11.23

[1]Nitrogen applied after crop emerged.

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11. The optimal rate of fertilization usually is considered to be the rate that maximizes profits for producers. This is estimated by fitting a

model to data collected at specific rates of fertilization and solving the model to identify the rate at which the marginal increase in costs of fertilization equals the marginal increase in value of the crop produced. Estimates of optimal rates of fertilization vary with the model used because each model imparts a subtle bias when describing yield response. Even subtle bias can result in important errors when estimating optimal rates because marginal increases in yield diminish with each successive increment of fertilizer applied and because the normal prices of corn and fertilizer are such that yields change relatively little with changes in N rates at optimal N rates.

12. More details concerning the methods used are available on Science Online.

13. The amount by which rates were reduced (56 kg N ha^{-1}) was selected because it is an easy quantity to remember when expressed in units used by producers (50 lb N $acre^{-1}$) and a number that often appears in calibrations for fertilizer applicators. The mean normal rate used by the cooperating producers is probably close to the mean rate applied for corn grown after soybean in Iowa in fields where no manure is applied. The National Agricultural Statistics Service (available online at http://www.usda.gov/nass/) estimates the mean rate at 143 kg N ha^{-1} for all corn in Iowa, but this estimate includes many fields where

rates of N fertilization are reduced to account for N applied with the manure.

14. Data reported by the National Agricultural Statistics Service indicate that the 10-year mean market value of corn grain during October and November in Iowa is US \$83.83 Mg^{-1} (available online at http://www.usda.gov/nass/). Prices during these months were used to separate activities associated with production and marketing of corn, where marketing includes consideration of grain storage costs. The reported mean price of fertilizer (i.e., the mean price for N as urea, urea-ammonium nitrate solutions, and anhydrous ammonia in the North Central U.S. Region during the years of this study) was US \$0.54 kg^{-1} N.
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Supporting Online Materials

The on-farm trials were conducted from 2000 through 2003 at sites selected to represent a wide range in soils extensively used for corn production in Iowa (Fig. 1). Except for nitrogen treatment, all management practices were those normally used by the cooperating producer. The producers were selected on the basis of interest and experience with yield-monitoring technologies.

All fertilizer treatments were applied in the spring, usually within 2 weeks of planting. Small amounts of N that were added as phosphorus fertilizer or starter were included in the rates shown. The fertilizer materials were those commonly used by producers in Iowa (anhydrous ammonia, aqueous solutions containing urea and ammonium nitrate, and solid urea). Each treatment was usually replicated 5 times in alternating strips. The width of the strip (6-18 m) was determined primarily by the width of the fertilizer applicator, which tends to be wider than the combines used during harvest. The treatment strips usually included two combine swathes. The lengths of the strips (usually >500 m) were determined by the length of the rows normally planted by the producer.

Different methods were used to align fertilizer treatments and combine swathes. On no-till fields, rows of plant stubble from the preceding crop were often used as guides when applying fertilizer and planting. Some producers had guidance systems based on GPS. On many fields, the lower rate of fertilizer was applied uniformly across the fields before planting and an extra 56 kg ha^{-1} was applied by following normal marks and wheel tracks made during planting. On many farms, the fertilizer treatments were applied by following rows and wheel tracks made during planting.

When the fertilizer treatments were applied, the position of each planned swath of the combine was marked by placing flags of an appropriate color at the ends of the field. These flags remained in the fields until harvest and were used to avoid possible errors at harvest. In a few trials, differences in width of fertilizer applicators and combines resulted in combine swathes that had a mixture of fertilizer treatments. Such swathes were included in the experimental plan but not used during data analysis.

During harvest, the producers maintained a constant combine speed while harvesting each strip and manually entered the strip treatment into the yield monitor in accordance with commonly used guidelines (*1*). The term "yield monitor", of course, usually denotes sensors that measure grain flow and moisture, a control panel for the operator, and a computer equipped with appropriate hardware and software (*2*). The producers used standard methods to calibrate the yield monitors. Our experience is that the errors in these calibrations are no greater than found in traditional field plot research.

Data were downloaded from the yield monitors to computers for processing and analysis. To aid in interpretation of the yield monitor data, aerial photographs of the fields were taken in August and qualitatively examined to identify irregularities (i.e., areas where plants were killed due to flooding, missing rows due to problems during planting or cultivating, extraordinary weed problems, etc.) that would introduce errors. Geographic Information Systems (GIS) were used to remove yield data that included problems associated with changes that occur at the beginning and end of strips or other problem areas identified by remote sensing.

Amounts of N harvested in grain were estimated by assuming that grain has an average of 1.5% N at 0% water content. The estimates recognize that grain is usually marketed at 15.5% moisture.

Analysis of variance (ANOVA) was preformed using Proc GLM (*3*) to determine the statistical significance of the differences between fertilizer treatments. The experimental design was a randomized complete block with sites as blocks and two experimental units within each site consisting of two sets of alternating strips. The fertilizer treatments were randomly assigned to the experimental units within each site. The F-test of fertilizer treatment was 6.83 with a p-value of <0.0001 and 75 degrees of freedom. A 95% confidence interval of the mean yield difference was 0.19 to 0.35 Mg ha^{-1}.

The methods used to measure yields in this study are difficult to compare to traditional methods because larger areas of land were involved. In traditional small-plot trials, where yields are measured by hand-harvesting, yield reductions at individual sites are usually significant at the

10% level only when greater than about 7% (*4, 5*). kg N and it represents a 3.2% reduction in mean grain yields.

Only two rates of N fertilization, both in the near-optimal range, were applied in our studies because our objective was to efficiently build on existing knowledge rather than to merely repeat what has been done in the past. Non-fertilized controls were avoided for several reasons; past studies have shown that applying no fertilizer is not a reasonable recommendation for corn grown after soybean in Iowa, rates of fertilization far below the near-optimal range increases problems of model bias when trying to interpret results within the near-optimal range, emphasis on the relatively large yield responses usually observed in response to low rates of fertilization makes it easy to over-estimate the benefits expected from higher rates, and the addition of unnecessary treatments decreases the ability to address spatial variability in N fertilizer needs. It should be noted that our method of analysis detects situation in which optimal rates of N fertilization are higher or lower than the two rates applied.

The analyses presented here were based on the simplifying assumption that producers will apply a single rate across an entire field and that the same rate would be applied to similar fields in all years. The experiments were designed for this purpose as well as to enable more complicated analyses designed to learn how profits for producers can be increased by varying rates of application to adjust for soil conditions within and among fields and weather conditions that make optimal rates of fertilization vary among years. Recent advances in fertilizer application technologies make it practical for producers to vary rates of fertilization within and among fields. The more complicated analyses will undoubtedly reveal ways that new application technologies can be used to further reduce mean rates of fertilization without loss of profit or yields. This possibility adds support to our conclusion that networks of precision farming trials offer a novel and effective way to reduce losses of N from agricultural soils to water supplies.

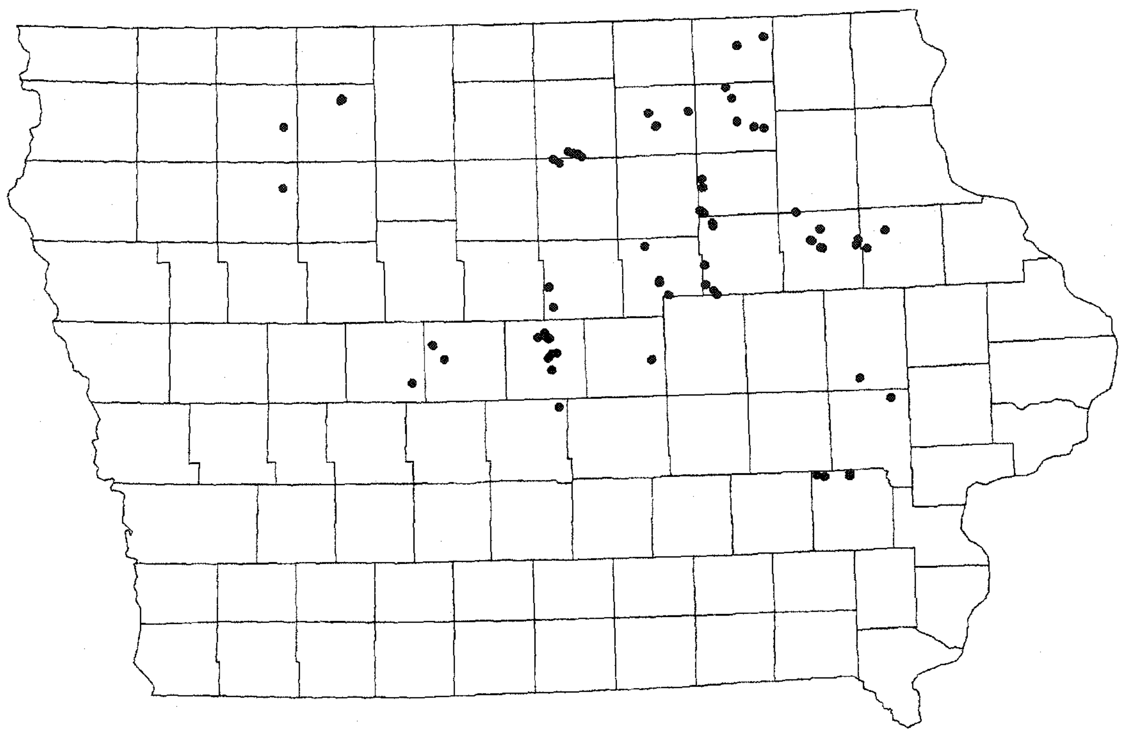

Figure 1. Map of Iowa showing sites of the on-farm trials.

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CHAPTER III. NITROGEN FERTILIZER NEEDS FOR CORN WHEN APPLICATION IS DELAYED UNTIL LATE SPRING

A paper to be submitted to Journal of Soil and Water Conservation

Bradley W. Van De Woestyne, Alfred M. Blackmer, and Tracy M. Blackmer

Abstract

On-farm trials using precision farming technologies were conducted at 30 sites in Iowa to evaluate the hypothesis that 112 kg N ha^{-1} (100 lb N $acre^{-1}$) is adequate to maximize profits for producers for corn grown after soybean if application is delayed until plants were about 15 cm (6 in) tall. The results show that reducing rates from 25% above to 25% below this rate did not reduce profits for producers or degrade soils. It is concluded that a management guideline given to producers call for more N than needed because they do not recognize the importance of timing of N applications on estimates of N fertilizer needs. The results demonstrate that publicly funded programs that reward producers for participating in regional programs to evaluate and improve N management practices offer a practical way to generate data needed to refine guidelines for N management as new knowledge and technologies continuously emerge.

Introduction

Recent studies identify early-season rainfall and associated losses of nitrogen (N) from soils as the primary factor responsible for year-to-year variability in nitrate concentrations in the cornfields and rivers of Iowa (Balkcom et al., 2003; Hansen et al., 2004). Key processes were identified as application of N weeks-to-months before plants begin rapid growth in late spring, marked variability among years in amounts of rainfall that occur during the spring, and leaching of nitrate as water moved from fields to rivers following rainfall. These observations are consistent with earlier reports of economic and environmental benefits from delaying applications of fertilizer N until plant growth begins (Ferguson et al., 1991; Jokela and Randall, 1989; National Research Council, 1993). The potential benefits of delaying fertilization are noteworthy because losses of N from agricultural soils have been identified as a cause of hypoxia in the Gulf of Mexico and a goal has been established to reduce these losses (Committee on Environment and Natural Resources, 2000; Council for Agricultural Science and Technology, 1999). The relatively great importance of early season rainfall as a factor affecting nitrate concentrations in rivers is easy to understand if it is recognized that corn producers in this region use similar management practices each year and follow similar guidelines when selecting rates of N fertilization.

Guidelines for N management commonly used in the Corn Belt (Hoeft et al., 2000) do not identify early-season rainfall as an important factor affecting N fertilizer needs for corn and do not indicate that N fertilizer needs should vary with time of N application. Relatively little effort has focused on estimating N fertilizer needs for corn in situations where applications of essentially all fertilizer N is delayed until plants are starting rapid vegetative growth (i.e., in late May or early June) in the Corn Belt. It seems likely there may be substantial benefits if the guidelines considered the importance of time of fertilizer application.

The results of recent on-farm trials using precision farming technologies (White and Blackmer, 1999) suggest that a recommendation to apply 112 kg N ha^{-1} (100 lb N $acre^{-1}$) in late May or early June would essentially maximize profits for producers growing corn after soybean. This possibility deserves attention because this rate supplies enough N to replace the amount removed in a 12.5 Mg ha^{-1} (200 bushel $acre^{-1}$) crop if it is recognized that 1 Mg of corn contains 12.5 kg N (1 bushel of grain contains 0.7 lb N) and assumed the soybean supplies 45 kg N ha^{-1} (40 lb N $acre^{-1}$). Currently used guidelines call for 21.4 kg N Mg^{-1} (1.2 lb N $bushel^{-1}$), which is 41% more N than needed to replace N removed by corn produced (Blackmer, 1987).

Here we report on-farm trials that evaluate the hypothesis that applications of 112 kg N ha^{-1} (100 lb N $acre^{-1}$) in late May or June is a reasonable recommendation for producers who grow corn after soybean in Iowa. The on-farm impacts of using this rate of fertilization was assessed by using precision farming technologies to quantify the impacts of reducing rates of fertilization from 25% above to 25% below the hypothesized reasonable rate. The results of this specific evaluation may apply to a relatively small geographic region, but the observations relating to the potential benefits of utilizing new technologies to evaluate and improve guidelines given to producers has much broader applicability and fundamental importance. The basic idea is that any guideline for N management should be considered only an estimate that needs constant evaluation.

Methods and Materials

The on-farm trials were conducted from 2000 through 2003 at sites selected to represent a wide range in soil types extensively used for corn production in Iowa (Fig. 1). Except for N treatments, all management practices were those normally used by the cooperating producers. The producers were selected on the basis of interest and experience with yield-monitoring technologies.

Fertilizer treatments were applied in late May or June, usually when the corn plants were about 15 cm (6 in) tall. The fertilizer materials were those commonly used by producers in Iowa, anhydrous ammonia or aqueous solutions containing urea and ammonium nitrate. Small amounts of N that were added with the phosphorus fertilizer or starter fertilizer were included in the rates reported. Each treatment was usually replicated 5 times in alternating strips. The width of each strip (6-18 m, 20-60 ft) was determined primarily by the width of the fertilizer applicator, which tended to be wider than the combines used during harvest. The treatment strips usually included two combine swathes. The lengths of the strips (usually >500 m, 1640 ft) were determined by the length of the rows normally planted by the producer.

When the fertilizer treatments were applied, the position of each planned swath of the combine was marked by placing flags of an appropriate color at the ends of the fields. These flags remained in the fields until harvest and were used to avoid possible errors at harvest. During harvest, producers maintained a constant combine speed while harvesting each strip and manually entered the strip treatment into the yield monitor in accordance with commonly used guidelines (Doerge, 1999). The term "yield monitor", of course, usually denotes sensors that measure grain flow and moisture, a control panel for the operator, and a computer equipped with appropriate hardware and software (Morgan and Ess, 1997).

Data were downloaded from yield monitors to computers for processing and analysis. To aid in interpretation of the yield monitor data, aerial photographs of the fields were taken in August and qualitatively examined to identify irregularities (i.e., areas where plants were killed due to flooding, missing rows due to problems during planting or cultivating, extraordinary weed problems, etc.) that would introduce errors. Geographic Information Systems (GIS) were used to remove yield data that included problems associated with changes that occur at the beginning and end of the strips or other problems identified by remote sensing. The methods used to collect yield data in this study are difficult to compare to traditional methods because larger areas of land were involved. In traditional small-plot trials, where yields are measured by hand-harvesting, yield reductions at individual sites are usually significant at the 10% probability level only when greater than usually 7% (Fox et al., 2001; Piekielek et al., 1995).

Analysis of variance (ANOVA) was preformed using Proc GLM (SAS, 2002) to determine the statistical significance of the differences between fertilizer treatments. The experimental design was a randomized complete block with sites as blocks and two experimental units within each site consisting of two sets of alternating strips. The fertilizer treatments were randomly assigned to the experimental units within each site. Normal prices for corn used in calculations were the 10-year mean market value of corn grain during October and November for Iowa of US \$83.83 Mg^{-1} (\$2.13 bu^{-1}) (available online at http://www.usda.gov/nass/). Prices during these months are used to separate activities associated with the production and marketing of corn. The reported mean price of fertilizer was US \$0.54 kg N^{-1} (\$0.25 lb N^{-1}). This value is the mean price for N as anhydrous ammonia and aqueous solutions of urea and ammonium nitrate in the North Central U.S. Region during the years of this study. Amounts of N harvested in grain were estimated by assuming that grain has an average of 1.5% N on an oven dry basis, or 1.3% at 15.5% moisture.

Results and Discussion

Rates used by the producers (Table 1) were near the target rates (25% less and 25% greater than 112 kg N ha^{-1}, 100 lb N $acre^{-1}$). These rates varied slightly from the target rates because of variability in calibration settings for each applicator and because additional N applied with phosphorus fertilizer or starter fertilizer at planting was included.

Mean yields of grain were 10.46 Mg ha^{-1} (167 bu $acre^{-1}$) at the higher rate and 10.23 Mg ha^{-1} (164 bu $acre^{-1}$) at the lower rate. The mean yield difference was statistically significant ($p=<0.0001$). The mean decrease in yield (0.23 Mg ha^{-1}, 3.6 bu $acre^{-1}$) had a 95% confidence interval of 0.14 to 0.31 Mg ha^{-1}(2.3 to 5.0 bu $acre^{-1}$). At normal prices for grain and fertilizer, however, the mean reduction in fertilizer cost (\$29.16 ha^{-1}, \$11.81 $acre^{-1}$) was greater than the reduction in mean value of crop (\$18.94 ha^{-1}, \$7.67 $acre^{-1}$). The reduction in rate of fertilization, therefore, would not have resulted in a reduction of mean profits for producers.

It is unlikely that higher rates of fertilization would have increased profits for producers because it is well established that, especially when data from many sites are considered, each successive incremental increase in rate of fertilization produces a smaller increase than the last. Analysis of this trend indicates that two-thirds of the yield increase observed in our study would be obtained by applications of 112 kg N ha^{-1} (100 lb N $acre^{-1}$), the rate under evaluation. It is clear, therefore, that the rate of 112 kg N ha^{-1} (100 lb N $acre^{-1}$) would have essentially maximized profits for producers.

Reducing rates of fertilization from 142 kg N ha^{-1} (127 lb N $acre^{-1}$) to 88 kg N ha^{-1} (79 lb N $acre^{-1}$) decreased estimated amounts of N harvested in grain by only 3 kg N ha^{-1}(3 lb N $acre^{-1}$). A similar decrease in amount probably occurred in corn residues left in the field after harvest. The reduction in rates of fertilization, therefore, had the potential to reduce the amounts of "residual" nitrate in soils at the end of the season by about 48 kg N ha^{-1} (42 lb N $acre^{-1}$). Any potential reduction in amounts of soil nitrate is desirable because rainfall and transpiration patterns are such that water moving through soils is most likely to leach nitrate from soils between cropping seasons in this region (Huang et al., 2001; Stanford, 1982).

Reductions in residual nitrate should be expected to have no important effects on fertilizer needs for the next crop because fertilizer N is neither needed nor applied for soybean crops, which can obtain adequate N through symbiotic relationships with nitrogen-fixing microorganisms. Because soybean plants efficiently utilize any nitrate that is in soils (Welch, 1979), residual nitrate from one corn crop should be expected to have minimal effects on the fertilizer needs for the next corn crop. It is noteworthy that corn grown after soybean receives most of the fertilizer N applied in the Corn Belt.

Removal of 128 kg N ha^{-1} (114 lb N $acre^{-1}$) during grain harvest in fields where only 88 kg N ha^{-1} (79 lb N $acre^{-1}$) was applied should not be considered evidence that the lower rate resulted in an undesirable depletion of soil N or degradation of soil quality. It is well established that estimates of fertilizer needs should be reduced when corn follows soybean rather than corn and that this reduction is necessary to account for the direct or indirect effects of soybean plants on supplies of plant-available N for the next crop (Green and Blackmer, 1995; Hoeft and Peck, 2002). This reduction is often described as a fertilizer-N "credit" from soybean and is often estimated to be about 45 kg ha^{-1}. Such credits illustrate the great importance of adjusting estimates of N fertilizer need to consider previous crops and other factors that are known at the time of fertilization.

The mean reduction in yields (0.23 Mg ha^{-1}, 3.6 bu $acre^{-1}$ or 2.4%) observed in this study probably is greater than the mean reduction in yields that would occur if all corn after soybean in Iowa received 88 kg N ha^{-1} (79 lb N $acre^{-1}$) after the crops emerged. Many crop producers are currently using N fertilization practices that are less efficient than studied here. Fertilizer N is often applied in the fall (about 6 months before plants begin rapid growth and uptake of N) and losses of fertilizer N often result in 20% loss of yield on years with above-normal amounts of spring rainfall (Hoeft et al., 2000; Vetsch and Randall, 2004). Recent studies (Balkcom et al., 2003) have linked losses of early-applied fertilizer N during spring rainfall (i.e., before plants need much fertilizer) to high concentrations of nitrate in rivers and deficiencies of N in cornfields. Fields receiving fall applications of fertilizer N were not included in this study because we reasoned that fertilizer needs should be estimated from data collected when relatively efficient fertilization practices are used.

Estimates of fertilizer needs are formally expressed in "recommendations" or "guidelines" developed and promoted by government groups and must be followed by crop producers otherwise entitled to government payments (USDA Natural Resource Conservation Service, 2001). The most commonly used guidelines are based on the assumption that N fertilization rates should be proportional to the yield levels obtained within a given soil type or region. For much of the Corn Belt, guidelines have indicated that 21.4 kg N is needed per Mg of grain produced (1.2 lb N bushel^{-1}) (Hoeft et al., 2000; USDA Natural Resource Conservation Service, 1999). Such guidelines should be questioned because only 12.5 kg N is harvested in each Mg of grain (0.7 lb N bushel^{-1}), because the mean high rate of fertilization was only 79% of that recommended, and because reducing this rate by 54 kg N ha^{-1} (48 lb N acre^{-1}) did not result in a loss of mean profits for the producers. These observations suggest that currently used guidelines call for more N than is needed when applications are delayed.

There is evidence that the efficiency of N fertilization has increased in recent years because yields are increasing at a mean rate of 0.12 Mg ha^{-1} $year^{-1}$ (2 bu $acre^{-1}$ $year^{-1}$). Increases in yield levels over the past 2 decades cannot be attributed to increases in N fertilization rates because mean rates of fertilization for the past 10 years (141 kg N ha^{-1}, 126 lb N $acre^{-1}$) are less than the mean rates (148 kg N ha^{-1}, 132 lb N $acre^{-1}$) during the preceding 10 years (Table 2). This increase in yields should be attributed to changes in cultural practices that increased the efficiency of N fertilization. Although there is no generally accepted way to define the efficiency of N fertilization, we assume that a fertilization practice can be considered more efficient if it reduces losses of N without reducing profits for the producer or quality of soil.

The largest yield loss resulting from the reduction of fertilizer N was 0.69 Mg ha^{-1} (11 bu $acre^{-1}$), and yield reductions greater than 0.36 Mg ha^{-1} (5 bu $acre^{-1}$) were observed at 6 sites. Although the higher rate of fertilization would have been profitable at these sites, these profits could not be obtained unless responsive sites could have been identified before the fertilizer was applied. Such responsive sites usually cannot be identified at this time, however, because responses to fertilizer are determined by many factors (i.e., weather, insects, diseases, etc.) that occur during the growing season. The problem of unavoidable uncertainty when estimating optimal rates of fertilization is widely recognized and usually addressed by recommending extra N, often called "insurance N", to avoid severe economic penalties associated with yield loss due to deficiencies of N (Babcock, 1992; Barber, 1973). Results of our studies suggest that delaying applications of fertilizer N should be considered an effective way to decrease amounts of insurance N needed. Because currently used guidelines for N management do not explain how optimal rates of insurance N are estimated, it is not possible to explain exactly why existing guidelines call for more N than seems to be needed. Our results suggest, however, that a rate of 112 kg N ha^{-1} (100 lb N $acre^{-1}$) may include enough "insurance N."

A critical problem in refining estimates of fertilizer needs has long been the high cost of measuring yield response to fertilizer N across the wide range of conditions found in production agriculture. This problem is exacerbated by rapid changes in the production practices most commonly used and alternative practices available for use. Our study demonstrates that organized networks of producers with precision farming technologies can rapidly and efficiently evaluate alternative management practices within a region or watershed and identify those which increase the efficiency of N fertilization and thereby increase profits for producers while reducing losses of fertilizer N to the environment. A noteworthy advantage of this approach is that observations can be made at a sufficient number of sites to enable assessment of fertilizer needs that address uncertainty due to factors that cannot be predicted at the time of fertilization.

Summary and Conclusions

Programs to help corn producers to continuously evaluate and improve their N fertilization practices seem to have much greater potential for reducing losses of N from agricultural soils than programs that specify amounts of N that can be applied. Programs to improve the guidelines given to producers should be clearly distinguished from efforts to get producers to follow guidelines. This approach deserves attention as governments move toward requiring crop producers to follow nutrient management guidelines. A key problem solved by this approach is that current guidelines seem to call for too much fertilizer N and there does not appear to be an alternate way to generate guidelines that keep pace with increasing knowledge and new technologies that can be used to increase the efficiency of N fertilization practices.

The results support the hypothesis that 112 kg N ha^{-1} (100 lb N $acre^{-1}$) is adequate to maximize profits for Iowa producers growing corn after soybean when applications are delayed until plants are about 15 cm (6 in) tall. The results indicate that current guidelines for N management call for more N than is really needed for this crop, and it suggests need to re-examine the methods used to develop the current guidelines. Particular attention needs to focus on how optimal rates of “insurance N” are estimated and how the guidelines are updated for the potential improvements in fertilization efficiency with advances in knowledge and technologies. The results demonstrate that organized networks of producers using precision farming technologies offer a new and efficient way to generate the data needed to generate guidelines that help producers reduce environmental problems associated with the use of N fertilizers without decreasing profitability or competitiveness of crop production.

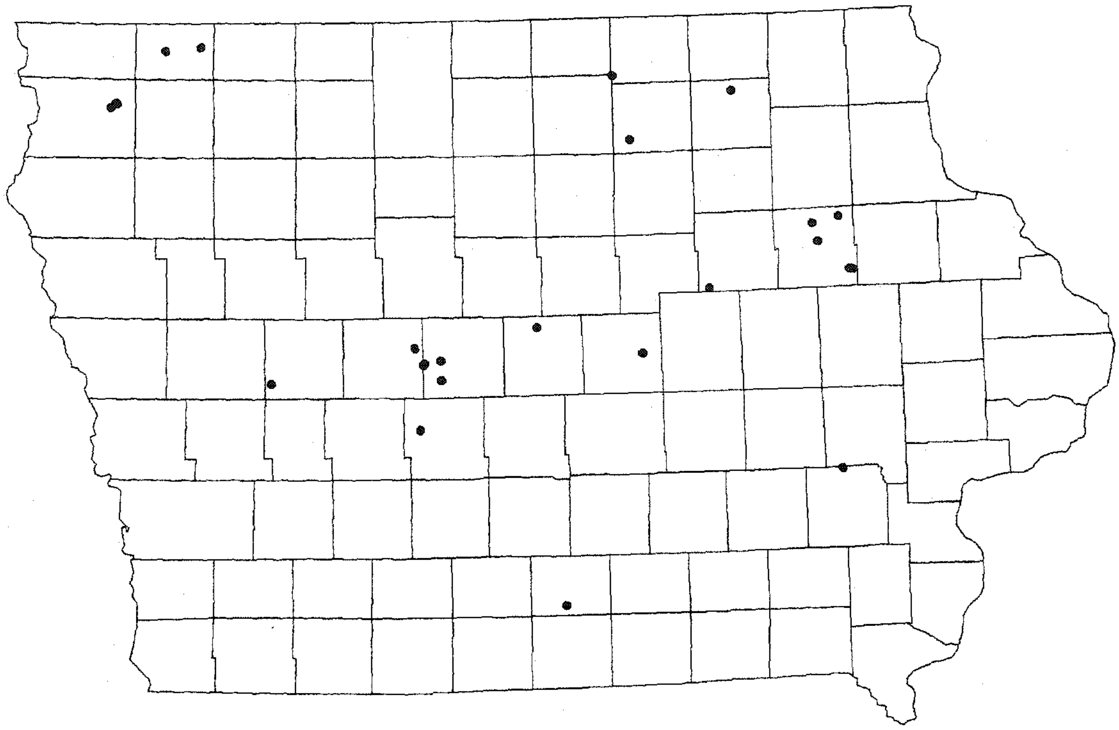

Figure 1. Map of Iowa showing the sites of the on-farm trials.

Table 1. Summary of rates of N fertilization and corn grain yields by site.

	Fertilizer N		Yield	
County (Year)	Low Rate	High Rate	Low Rate	High Rate
	-------- kg N ha^{-1} --------		-------- Mg ha^{-1} --------	
Osceola (02)	75	131	9.67	10.16
Floyd (01)	84	140	10.63	11.12
Boone (03)	84	140	11.61	11.95
Boone (03)	84	140	12.17	12.24
Boone (03)	84	140	11.58	11.89
Greene (02)	84	140	10.01	10.20
Greene (02)	84	140	11.63	11.97
Greene (02)	84	140	10.90	11.14
Osceola (02)	84	140	7.98	8.35
Lucas (01)	84	140	9.14	9.78
Boone (01)	84	140	9.02	9.28
Boone (01)	84	140	8.32	8.61
Story (01)	84	140	9.21	9.90
Sioux (02)	84	140	10.06	9.91
Sioux (02)	84	140	8.85	9.02
Sioux (02)	84	140	9.27	9.39
Dallas (01)	84	140	8.54	8.69
Buchanan (01)	90	123	11.25	11.76
Carroll (02)	90	151	10.39	10.63
Buchanan (00)	90	123	9.01	9.21
Marshall (01)	90	146	10.76	10.93
Washington (01)	90	146	14.31	14.63
Bremer (03)	92	148	8.54	8.63
Sioux (03)	93	154	10.63	10.53
Sioux (03)	93	154	10.37	10.32
Mitchell (01)	95	123	10.62	10.66
Dallas (02)	96	152	8.45	8.53
Chickasaw (02)	101	157	9.30	9.47
Buchanan (01)	104	144	11.63	11.51
Buchanan (02)	107	163	13.09	13.35
Mean	88	142	10.23	10.46

Table 2. Trends in nitrogen fertilizer rate and corn production in Iowa.

Period	Rate of N fertilization	Corn Grain Yield
Year	kg N ha^{-1}	Mg ha^{-1}
1964 - 1968	86	5.38
1969 - 1973	120	6.38
1974 - 1978	132	5.78
1979 - 1983	154	7.11
1984 - 1988	154	7.34
1989 - 1993	139	7.35
1994 - 1998	139	8.70
1999 - 2003	143	9.49

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CHAPTER IV. BENEFITS OF NITRIFICATION INHIBITOR AS ASSESSED BY PRODUCERS USING PRECISION FARMING TECHNOLOGIES

A paper to be submitted to Crop Management

Bradley W. Van De Woestyne, Alfred M. Blackmer, and Tracy M. Blackmer

Abstract

Nitrification inhibitors are often applied with anhydrous ammonia to reduce losses of N during corn production, but the benefits have not been clearly established. We explored the potential of using precision farming technologies in on-farm trials to assess these benefits of using nitrapyrin in fields having calcareous and non-calcareous soils in Iowa. The results show that the inhibitor was not profitable to use under the conditions studied. However, the results clearly demonstrate how precision farming technologies enable groups of producer working together can easily assess the benefits of nitrification inhibitors under conditions important to them.

Introduction

Nitrification inhibitors added to anhydrous ammonia have the potential to decrease losses of nitrogen (N) during corn production and increase profits for producers. The inhibitors are intended to reduce losses of N by denitrification and leaching before plants grow. The problem they address is clearly important in Iowa because recent studies indicate that losses of N associated with spring rainfall are a key factor affecting supplies of N for corn growth (10) and concentrations of nitrate in rivers (1). Results of field evaluations of nitrification inhibitor performance for corn, however, have been variable (4, 5, 12), so the benefits of using the inhibitor have not been clearly established.

Soil pH and carbonate content were recently identified as an important factor affecting rates of nitrification and potential for losses of N (6). Higher pH values and carbonates tend to increase rates of nitrification and, therefore, increase the potential for losses of N during spring rainfall. There is special need, therefore, to assess the benefits of inhibitors in areas with calcareous soils. Calcareous soils contain sufficient $CaCO_3$ and $MgCO_3$ to effervesce visibly when treated with a strong acid (11) and usually have pH values > 7.5. Many fields in central Iowa have calcareous and mildly acidic soils intermingled in complex spatial patterns (8, 9). Methods for assessing the benefits of using a nitrification inhibitor in such fields deserve attention.

Our objective in this paper is to explore the potential of using precision farming technologies in on-farm trials to assess the benefits of using a nitrification inhibitor with anhydrous ammonia in central Iowa. Our reasoning is that this approach may make it practical to make many observations and thereby help to address the problem of uncertainty concerning the benefit of using an inhibitor.

Materials and Methods

On-farm trials were established to compare anhydrous ammonia with and without nitrapyrin under conditions normally used for corn production in central Iowa. The nitrapyrin was applied at a rate of 0.5 lb acre^{-1} as recommended by the manufacturer [2-chloro-6-(trichloromethyl) pyridine, Dow AgroSciences, Indianapolis, IN]. The trials were conducted from 2002 through 2004 in fields selected to include calcareous soils (Fig. 1). The producers were selected on the basis of interest and experience with yield-monitoring technologies. Except for N treatment, all management practices were those normally used by the cooperating producers.

The fertilizer treatments were applied either in the fall or spring at rates normally used by the producers (Table 1). Small amounts of N added as phosphorus fertilizer or starter are included in the rates shown. The treatments (with or without inhibitor) were applied in alternating strips usually replicated 5 times. The width of the strip (40-90 ft) was determined primarily by the width of the fertilizer applicator, which tended to be wider than the combines. Each treatment strip included at least two combine swathes. The lengths of the strips (usually >1640 ft) were determined by the length of the rows normally planted by the producer.

Different methods were used to align fertilizer treatments and combine swathes. On strip- or ridge-till fields, rows of plant stubble from the preceding crop were used as guides when applying fertilizer and planting. In other fields GPS was used to record the location of the treatment strips. At some sites differences in width of fertilizer applicators and combines resulted in combine swathes that had a mixture of fertilizer treatments. Such swathes were included in the experimental plan but not used during data analysis.

During harvest, the producers maintained a constant combine speed while harvesting each strip in accordance with commonly used guidelines (3, 7). Data were downloaded from the yield monitors to computers for processing and analysis. To aid in interpretation of the yield monitor data, aerial photographs of the fields were taken in August and qualitatively examined to identify irregularities (i.e., areas where plants were killed due to flooding, missing rows due to problems during planting or cultivating, extraordinary weed problems, etc.) that would introduce errors. Geographic Information Systems (GIS) were used to remove yield data that included problems associated with changes that normally occur at the beginning and end of strips or other problem areas identified by remote sensing.

Analysis of variance (ANOVA) was preformed using Proc GLM in SAS (SAS Institute, Cary, NC) to determine the statistical significance of the differences between fertilizer treatments. The experimental design was a randomized complete block with sites as blocks and two experimental units within each site consisting of two sets of alternating strips. The fertilizer treatments were randomly assigned to the experimental units within each site. Normal prices for corn used in calculations were the 10-year mean market value of corn grain during October and November for Iowa of US \$2.13 bushel^{-1} (available online at http://www.usda.gov/nass/). Prices during these months are used to separate activities associated with the production and marketing of corn. The price of nitrapyrin was assumed to be \$8.00 acre^{-1} in all calculations.

Maps of yield response to nitrapyrin were created by dividing the field into cells. Adjacent treatment strips (a strip with inhibitor and a strip without inhibitor) were divided into 40 ft cells to form a pair of cells. A mean yield for each cell was calculated by using yield points contained within the cell, and a yield response for each pair of cells was calculated by subtracting the mean yield with inhibitor from the yield without inhibitor. The position of each pair of cell was marked by a point on the map and the points were colored to identify whether or not nitrapyrin was profitable.

Results and Discussion

Mean yields were 183.8 bushel acre^{-1} with the nitrification inhibitor and 182.5 bushel acre^{-1} without. The difference (1.3 bushel acre^{-1}) was not statistically significant (p=0.3236). A 95% confidence interval of the mean yield difference was -1.4 to 3.8 bushel acre^{-1}.

The results of this study are noteworthy because they were during years with above-average amounts of spring rainfall (Fig. 2) and, therefore, above-average opportunity for the inhibitor to express benefits. Moreover, the trials were conducted in fields having calcareous soils, which have been identified as a severe problem with respect to losses of fall-applied anhydrous ammonia (6).

Use of the nitrification inhibitor was not profitable for the producers at normal prices of the inhibitor and grain. At normal prices for grain, a yield increase of 3.8 bushel acre^{-1} would be necessary to pay for the inhibitor. Each dollar the producer spent on inhibitor returned a mean of only $0.32 in additional grain. The overall net value of crop was reduced by 1.5% when the inhibitor was used.

Maps of yield response to inhibitor overlaid on soil survey maps reveal no obvious relationships between soil types and yield responses (Fig. 3). These observations suggest that it would not be a simple task to improve the net benefits of inhibitors by using variable rate application technologies. However, the maps do seem to reveal complex patterns of yield response within the trial. This finding could be explained if rates of nitrification, effectiveness of inhibitor, and potential for loss of N from soil interacted in complex ways with soil pH, organic matter content, landscape position, and other factors. It seems that spatial patterns probably occurred, but these patterns are too complex to characterize by the methods used.

The ability to detect significant small yield responses to nitrapyrin was greater in our study than usually attained in studies using traditional small-plot techniques. A yield increase of 2.6% would be considered significant at a 95% confidence level in our study. In a survey of relevant published studies Blackmer (2) found that the nitrification inhibitor had to increase yields by a mean of 22% to be considered statistically significant by the original investigators, who used 90 or 95% confidence levels. Greater ability to detect smaller yield responses to treatments is important because it removes uncertainty when estimating the value of the treatment to producers.

It should be obvious to everyone involved in crop production that our finding that the nitrification inhibitor was not profitable to use across the range of conditions studied should not be extrapolated to all conditions. Similarly, the results should not be extrapolated to all conditions if we had found that the inhibitor was profitable. The most important observation from this study, therefore, is that producers can use precision farming technologies in on-farm trials to assess the benefits of using nitrification inhibitors under conditions important to them. The finding that mapping the benefit of nitrapyrin did not reveal clear spatial patterns in the soil association we studied should not be considered evidence that clear spatial patterns would not appear in other soil associations.

Conclusions

Nitrapyrin reduced profits for corn producers under the range of conditions studied. The most important observation made, however, is that precision farming technologies enable groups of producers working together to easily assess the benefits of nitrification inhibitors in their fields.

Table 1. Summary of date and rate of fertilization, soils, and corn grain yield by site.

County (tillage)[1]	Crop Year	Date Applied	Fertilizer N Rate	Soil Map Units[2] (% of area)	Yield With Inhibitor	Yield Without Inhibitor
			lb N acre^{-1}		------- bushel acre^{-1} -------	
Hamilton (R)	2003	4/14/03	110	1507 (51), 288 (22), 6 (4)	157	158
Hamilton (R)	2003	4/14/03	110	1507 (100)	168	165
Webster (C)	2002	11/16/01	125	107 (34), 507 (28), 55 (15)	176	175
Hamilton (R)	2004	6/18/04	128	288 (49), 388 (32), 1507 (16)	179	175
Hamilton (R)	2003	4/14/03	110	52 (53), 1507 (33)	179	180
Hamilton (R)	2004	6/18/04	128	1507 (62), 288 (38)	181	175
Webster (C)	2002	11/16/01	125	507 (43), 107 (34), 55 (6)	182	183
Hamilton (R)	2003	4/14/03	110	1507 (91), 288 (5), 6 (4)	183	184
Boone (C)	2002	11/20/01	142	95 (60), 507 (16), 138 (12)	190	193
Boone (C)	2003	11/15/02	137	95 (36), 507 (27), 138 (12)	191	181
Boone (S)	2002	10/25/01	171	107 (53), 138 (28), 55 (18)	196	197
Story (S)	2002	11/06/01	171	507 (55), 138 (15), 55 (15)	204	203
Boone (C)	2004	11/19/03	140	95 (57), 138 (17), 507 (16)	205	205
Mean			131		183.8	182.5

[1] R, Ridge; C, Conventional; S, Strip

[2] 6, Okoboji; 52, Bode; 55, Nicollet; 95, Harps; 107, Webster; 138, Clarion; 288, Ottosen; 388, Kossuth; 507, Canisteo; 1507, Brownton.

Soil map units 95, 507, and 1507 are classified as calcareous.

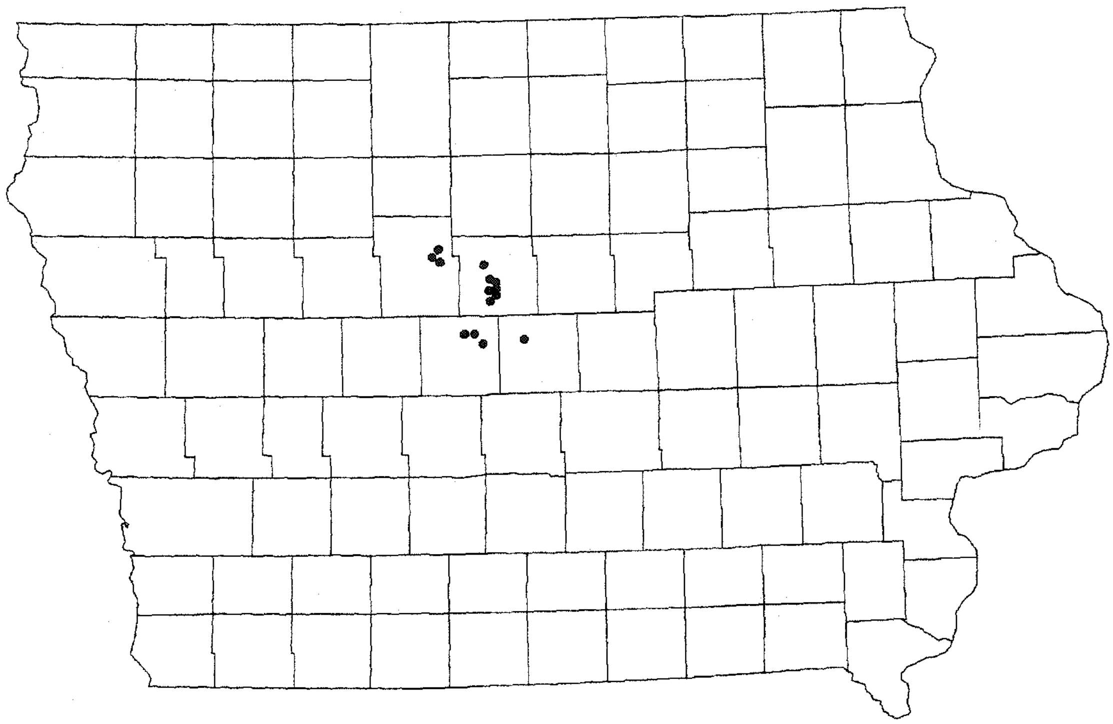

Figure 1. Map of Iowa showing sites of the on-farm trials.

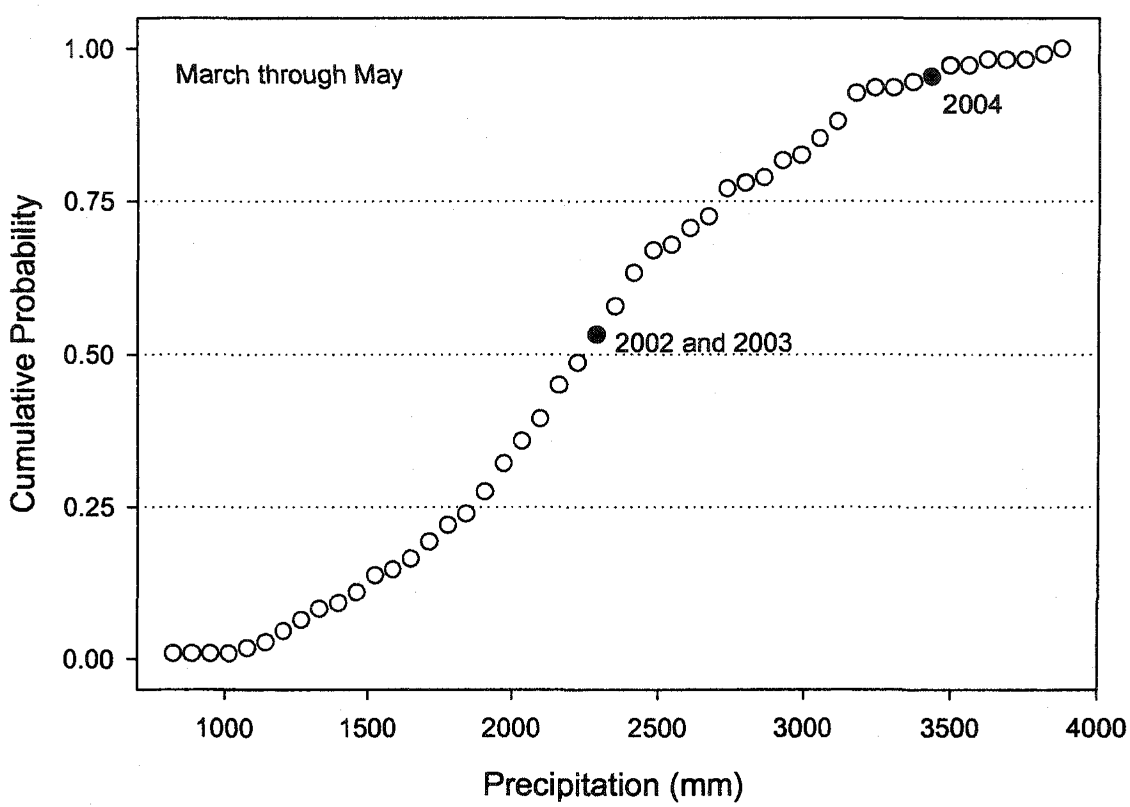

Figure 2. Cumulative probability distribution for March through May rainfall for the past 30 years in the region where on-farm trials were located.

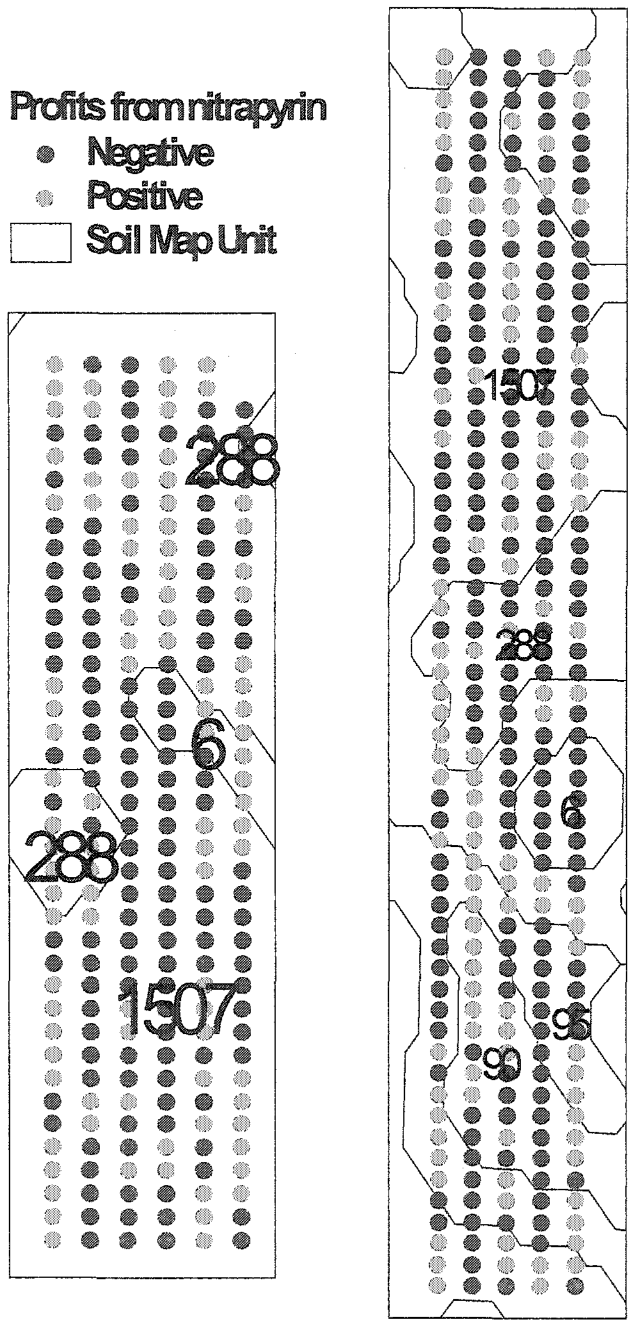

Figure 3. Field map showing yield response to nitrapyrin observed in cells that form a grid pattern.

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CHAPTER V. NITROGEN SUFFICIENCY ASSESSMENT IN CORNFIELDS FERTILIZED BY INJECTING LIQUID SWINE MANURE

A paper to be submitted to Agronomy Journal

Bradley W. Van De Woestyne, Alfred M. Blackmer, and Tracy M. Blackmer

Abstract

Levels of nitrogen (N) sufficiency in cornfields fertilized with animal manure vary greatly and this variation causes many producers to apply additional fertilizer N. On-farm trials were conducted with precision farming technologies to assess N-sufficiency levels in cornfields fertilized with injected liquid swine (*Sus scrofa*) manure as normally practiced in Iowa. Measuring yield responses showed that injected liquid swine manure supplied sufficient N for corn. Soil and cornstalk tests for nitrate independently assessed N-sufficiency and confirmed that the manure supplied sufficient N. Because the rates of manure-N applied were higher than usually needed to supply adequate N when commercial fertilizer is applied, however, the results suggest that liquid swine manure was not equivalent to the commercial fertilizers. This observation suggest that current guidelines for manure management should be questioned and that

producers have the ability to develop better guidelines by using precision farming technologies to assess N-sufficiency levels on their fields.

Introduction

The sufficiency of N for corn growth in fields treated with animal manure can be directly assessed by measuring plant responses to fertilizer N applied after the manure (Hansen et al., 2004). Such assessments can be considered to be *direct* because they do not rely on assumptions concerning the reliability of current guidelines for N management. Moreover, assessments of N-sufficiency level are not compromised when the addition of manure influences plant growth by altering factors other than supplies of N using this method. Supplies of N can be considered *sufficient* if the added fertilizer N does not significantly increase corn yields and *insufficient* (or deficient) when yields are increased.

The concept of nutrient-sufficiency levels is widely used and provides a theoretical basis for the use of soil and plant tissue testing to assess fertilizer needs (Blackmer, 2000; Bray, 1954; Macy, 1936). Basically, previously established relationships between soil- or tissue-test values are used to estimate nutrient-sufficiency levels or diagnose deficiencies at any individual site where samples are collected (Binford et al., 1992; Blackmer et al., 1989). Balkcom et al. (2003) recently showed how testing soils for nitrate in late spring and cornstalks for nitrate at the end of the season could be used to survey N-sufficiency levels and evaluate management practices across many different fields within a region. Use of these tests makes it possible to characterize N-sufficiency levels on scales that range from below optimal to above optimal. All assessments made in such surveys, however, must be based on assumptions that the soil and tissue tests are both reliable and properly calibrated for the specific conditions where they are used.

The traditional small-plot research methods used by Hansen et al. (2004) were extremely labor intensive, so it is impractical to obtain enough observations to adequately address the wide range of conditions likely to be encountered in cornfields treated with animal manure. Many observations are needed because many different factors (type of manure, method of manure application, uniformity of application, soil characteristics, weather, etc.) introduce great uncertainty into estimates of N supplied by manure and fertilizer needs after the manure is applied (Balkcom et al., 2003; Hansen et al., 2004; Schepers and Fox, 1989). This uncertainty deserves immediate attention because it prompts crop producers to apply manure at rates that supply more N than needed by crops and (or) to not make recommended downward adjustments in rates of N fertilization after manure is applied. Land treated with manure has been identified as a major source of nitrate in rivers (Jackson et al., 2000; Kalkhoff et al., 2000). Crop producers are now being required to develop nutrient management plans to reduce amounts of N lost from fields treated with animal manure (Animal Ag

Compliance Act State of Iowa Code, 2003; USDA Natural Resource Conservation Service, 2001).

Our objective in this paper is to explore the potential of using precision farming technologies in on-farm trials to directly assess N-sufficiency levels in cornfields fertilized by injecting liquid swine manure as normally practiced in Iowa. Our reasoning is that this approach may make it practical to make many observations and thereby help to address the problem of uncertainty concerning the rates of manure application needed to supply optimal amounts of N for corn. Moreover, these methods can be used to evaluate and improve the calibrations for soil and tissue tests for use under similar conditions where precision farming technologies are not used.

Many corn producers in Iowa are using combines with yield monitors and GPS, mapping yields in their fields, and these producers are interested in learning how to use these and related precision farming technologies to improve their management. Methods for using precision farming technologies for research are being developed (Bermudez and Mallarino, 2002; Blackmer and White, 1998; Fleming et al., 1998; Kitchen et al., 2003; Lowenberg-Deboer and Aghib, 1999; Stafford et al., 1998). Large quantities of liquid swine manure are produced in Iowa, and most of this is injected to soils for production of corn. Liquid manure is usually produced in relatively large and modern production facilities, which are prompting the greatest environmental concerns.

Materials and Methods

Liquid swine manure was injected with knives or disk-covers into soil during fall at 51 fields in Iowa. The rate of manure was constant across the field and was the rate normally used by the producer (Table 1). After corn emerged, flags were placed at the ends of the fields to identify treatment strips. The treatments were manure without fertilizer N and manure with commercially prepared fertilizer N. The width of the strip (9-20 m) was determined primarily by the width of the fertilizer applicator, which tended to be wider than combines used to harvest the strips. Each treatment strip included at least two combine swathes. The lengths of the strips (usually >500 m) were determined by the length of the rows normally planted by the producer. Except for N treatment, all management practices were those normally used by the cooperating producer.

Soil samples where collected in accordance with guidelines for the late-spring test for soil nitrate (Blackmer et al., 1989) from five test areas within strips where only manure was applied. Each sample consisted of at least 24 cores from the top 30 cm of the soil profile. The soils were air-dried, ground, and extracted with 2 M KCl. The extract was analyzed for nitrate by steam distillation (Keeney and Nelson, 1982).

Cornstalk samples were collected in accordance with guidelines for the end-of-season test for cornstalk nitrate (Blackmer and Mallarino, 1996) from the same test areas where the soil samples were collected and in adjacent test areas in strips where fertilizer N was applied (Binford et al., 1992). Each sample consisted of 15 20-cm sections of stalk beginning 15 cm above the surface of the soil. The stalks were air-dried, ground, and extracted with 2 M KCl. The extract was analyzed for nitrate by steam distillation (Keeney and Nelson, 1982).

During harvest, the producers maintained a constant combine speed while harvesting each strip in accordance with commonly used guidelines (Doerge, 1999; Morgan and Ess, 1997). Data were downloaded from the yield monitors to computers for processing and analysis. To aid in interpretation of the yield monitor data, aerial photographs of the fields were taken in August and qualitatively examined to identify irregularities (i.e., areas where plants were killed due to flooding, missing rows due to problems during planting or cultivating, extraordinary weed problems, etc.) that would introduce errors. Geographic Information Systems (GIS) were used to remove yield data that included problems associated with changes that normally occur at the beginning and end of strips or other problem areas identified by remote sensing.

Analysis of variance (ANOVA) was preformed using Proc GLM in SAS (SAS Institute, Cary, NC) to determine the statistical significance of the differences between fertilizer treatments. The experimental design was a randomized complete block with sites as blocks and two experimental units within each site consisting of two sets of alternating strips. The fertilizer treatments were randomly assigned to the experimental units within each site. Normal price for corn used in calculations was the 10-year mean market value of corn grain during October and November for Iowa of US \$83.83 Mg^{-1} (USDA-National Agricultural Statistics Service, 2004). Prices during these months are used to separate activities associated with the production and marketing of corn. The reported mean price of fertilizer was US \$0.54 kg N^{-1}. This value is the mean price for N as anhydrous ammonia and aqueous solutions of urea and ammonium nitrate in the North Central U.S. Region during the years of this study (USDA-National Agricultural Statistics Service). The cost of application of fertilizer N was assumed to be \$9.88 ha^{-1}.

Results and Discussion

Mean yields were 11.01 Mg ha^{-1} with manure and 11.19 Mg ha^{-1} with manure plus fertilizer N. The difference in yields (0.18 Mg ha^{-1}) was statistically significant ($p < 0.0001$). A 95% confidence interval of the mean yield difference was 0.09 to 0.28 Mg ha^{-1}. The value of the increase in yield is less than the costs of purchasing and applying additional fertilizer N, so application of additional fertilizer would have decreased profits for most producers. The cost of 56 kg of fertilizer N usually is about 0.36 Mg of grain and the cost of application is usually about 0.12 Mg of grain.

Our results show there was a poor relationship of yield response to additional fertilizer N and the rate of manure applied (Figure 1). This is noteworthy because current manure management guidelines for N in Iowa are based on application rate of manure. Producers are required to file and follow these management plans or be in violation of state law. A factor that did influence yield responses was early-spring rainfall (Table 2). This relationship follows the same trend found in Balkcom et al. (2003). Early-spring rainfall should be expected to correlate with evaluations of N-sufficiency because nitrate is susceptible to loss through leaching and denitrifcation following rainfall events.

The end-of-season cornstalk test correctly identified most fields where application of additional N was profitable for producers (Figure 2). Most fields (88 %) where only manure was applied fell into the marginal-through-optimal range and the percentages shifted toward excess when additional N fertilizer was applied (Table 3). This indicates the stalk test accurately assesses N-sufficiency in fields where manure has been applied and, more importantly, can be used to identify N management practices that supply excess amounts of N. Application of additional fertilizer N increased stalk nitrate concentrations at 86% of the sites (Figure 3). Producers who do not have yield monitors to conduct yield response trials can rely on the cornstalk test to evaluate N management practices on their farms.

The late-spring soil nitrate test usually was not needed in fields with injected liquid swine manure because manure usually supplied adequate N for plant growth and relatively few fields had great excesses of N (Figure 4). Table 4 shows the mean yield response to additional fertilizer N by categories based on soil test values. Mean yield increase were profitable in fields where soil test levels were < 10 mg N kg^{-1}. It would not be recommended, however, to collect soil tests from fields where liquid swine manure was injected because of the low frequency of fields testing in this range and the added expense of collecting soil samples. However, the test identified responsive sites reasonably well and could be used when large losses of N are suspected (i.e., large amounts of early-spring rainfall). The test also showed a relationship to the end-of-season test for cornstalks (Figure 5).

The mean rate of manure N application in this study is much higher than the rate of fertilizer N that is needed to attain N-sufficiency levels that maximize profits when applications are made in the spring (Van De Woestyne et al., 2005a; Van De Woestyne et al., 2005b). The finding that the rate of manure N required to attain the desired N-sufficiency levels is higher with manure than fertilizer and should be expected for several reasons. First, some of the N in manure is in organic forms that are not mineralized rapidly enough for the first crop after application. Second, the manure contains organic carbon that should be expected to immobilize inorganic N added with the manure. Third, the organic carbon should be expected to promote denitrification of nitrate when injected into bands below the soil surface. And fourth, the manure was applied in the fall so some losses should be expected during spring rainfall.

Conclusions

The data collected in this study indicate need to question guidelines based on the assumption that a kg of N in manure is equivalent to a kg of N in fertilizer. A more rational way to estimate amounts of manure N needed for corn is to assess the N-sufficiency levels attained when various amounts of manure are applied and select the rates of manure N application most likely to attain the desired N-sufficiency level. Although this approach was not practical in the past, it is practical today because producers have the ability to assess N-sufficiency levels by using precision farming technologies on their fields.

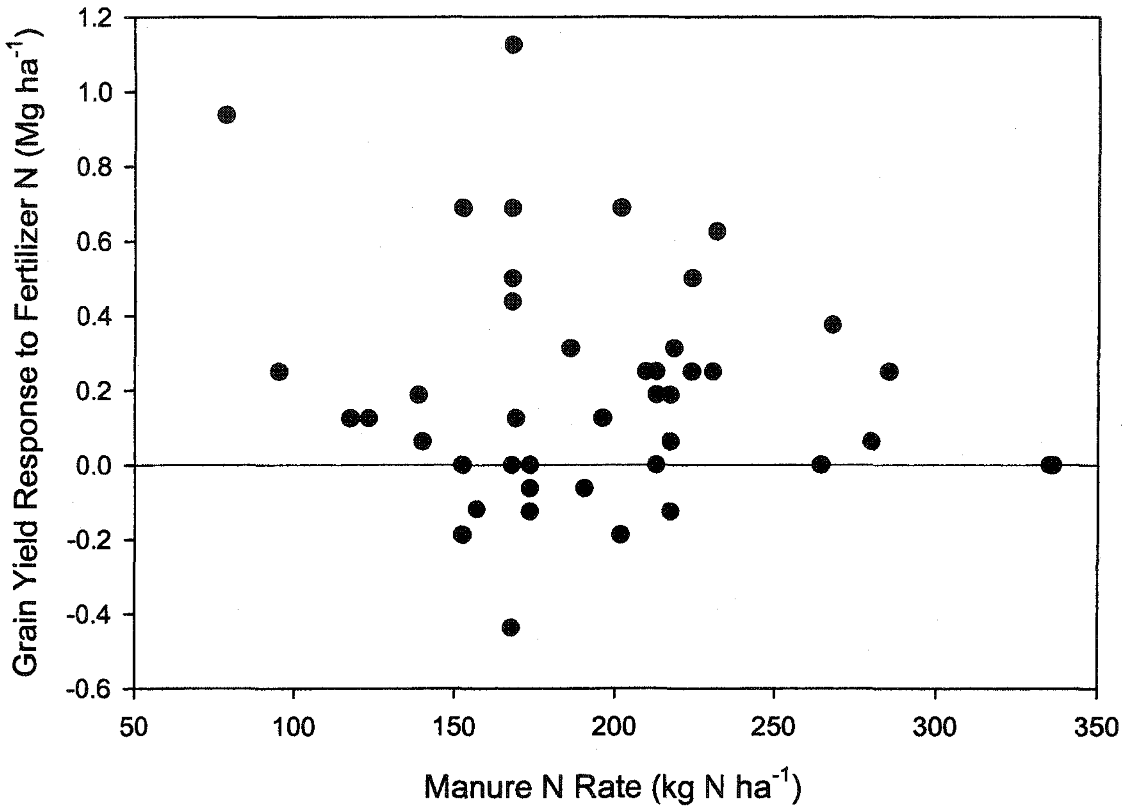

Figure 1. Relationship between corn yield responses to fertilizer N and rates of manure N calculated from results of manure analysis.

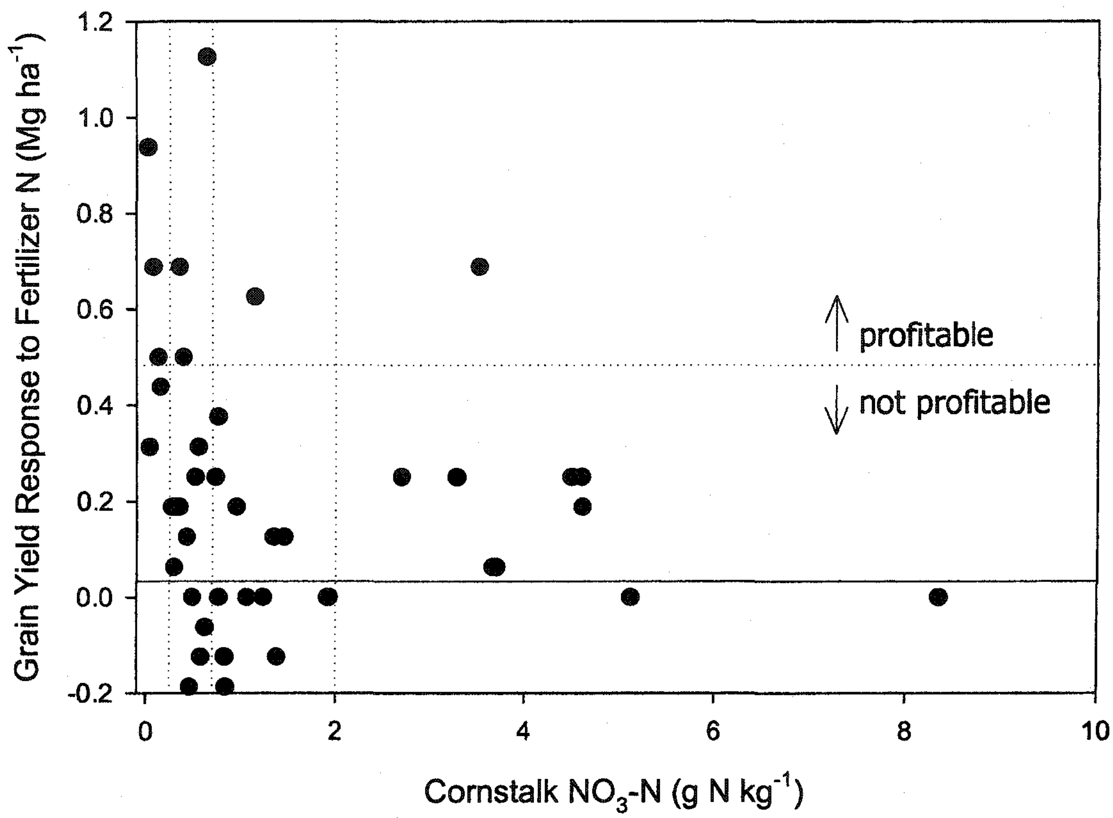

Figure 2. Relationship between corn yield responses to fertilizer N and nitrate concentrations in cornstalks collected after physiological maturity.

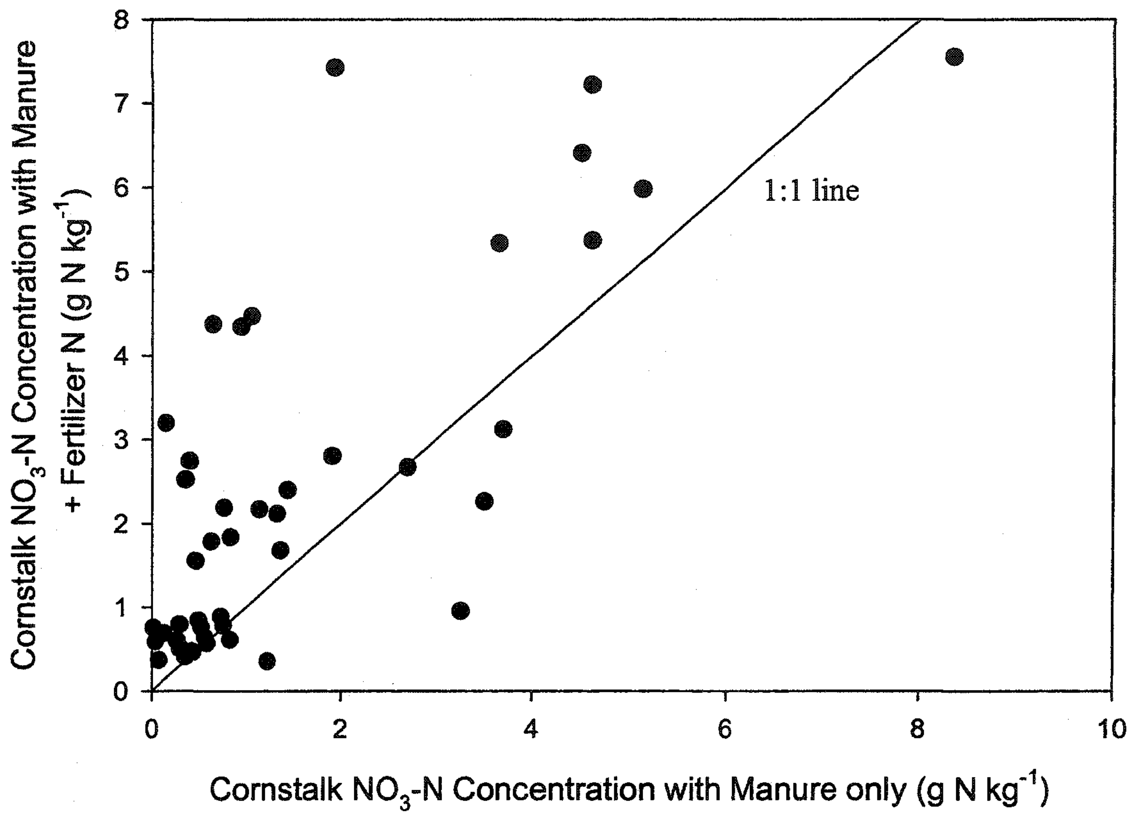

Figure 3. Relationship between nitrate concentrations in cornstalks with manure and with manure plus additional fertilizer N.

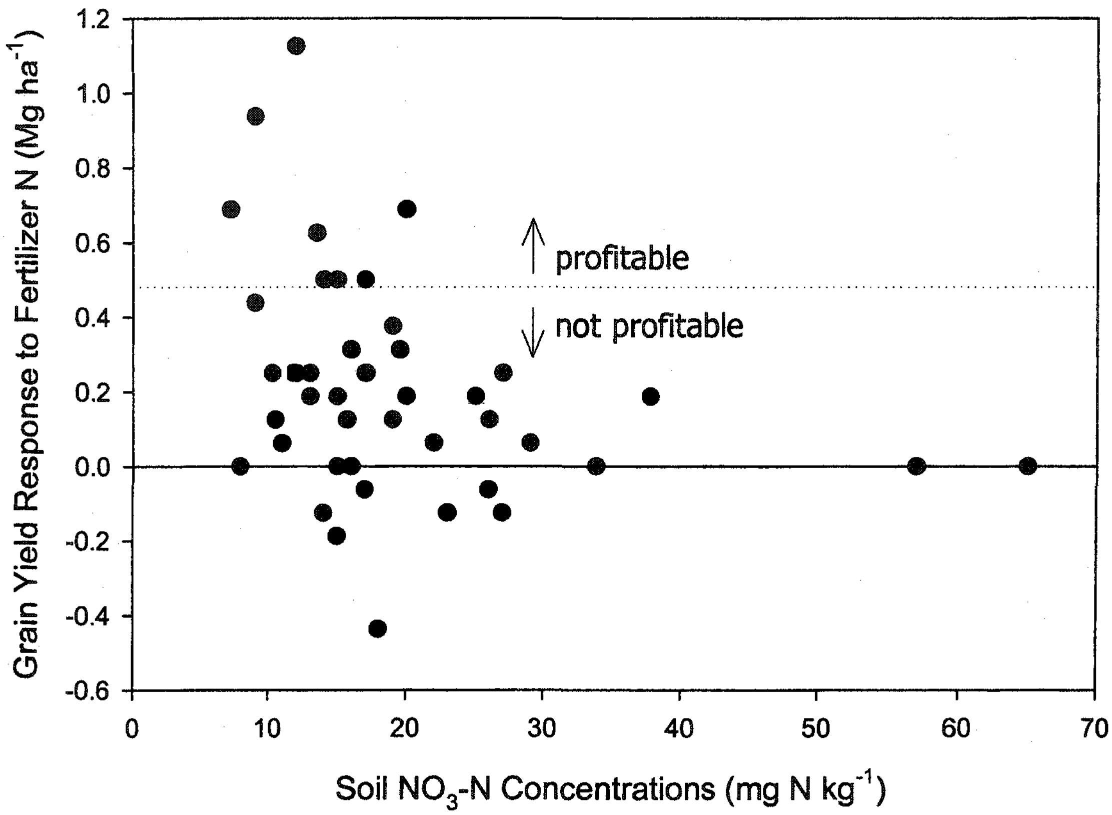

Figure 4. Relationship between corn yield responses to fertilizer N and nitrate concentrations from samples collected from the surface 30-cm of soil.

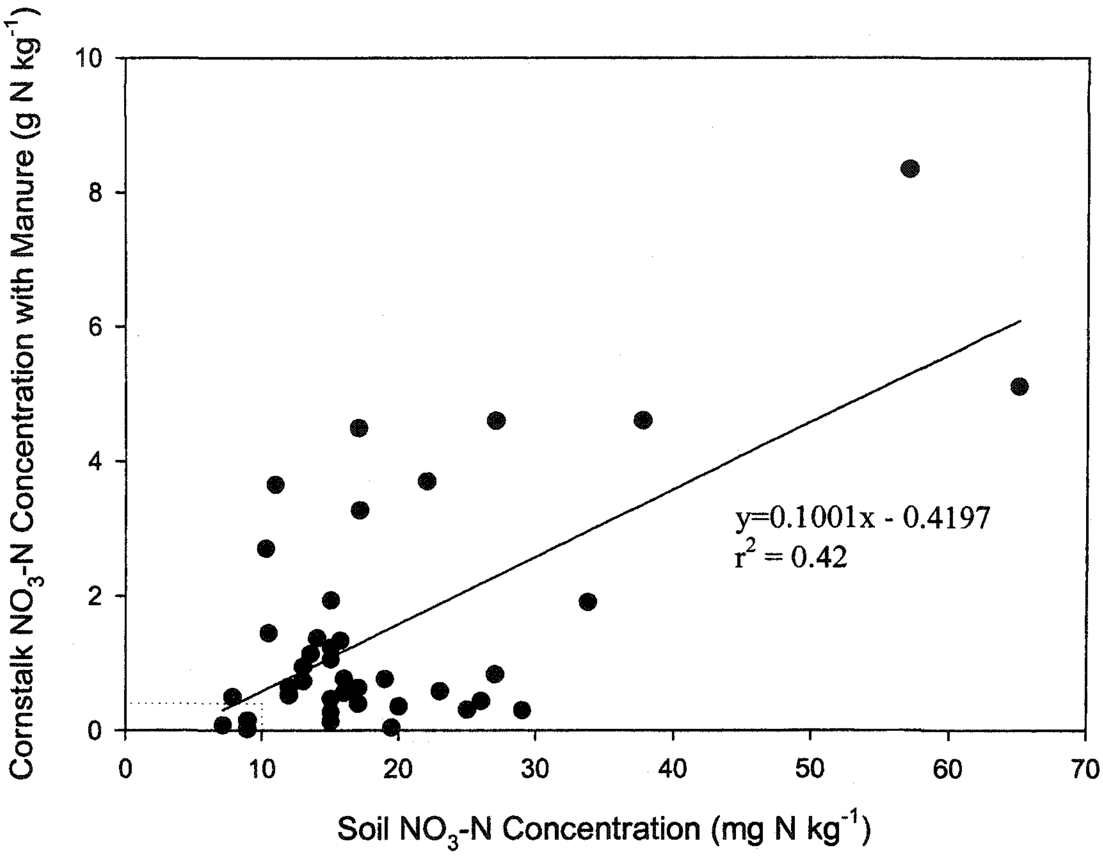

Figure 5. Relationship between nitrate concentrations in cornstalks with manure and nitrate concentrations from samples collected from the surface 30-cm of soil.

Table 1. Summary of rate, soil nitrate, yield, and stalk nitrate of on-farm trials.

County	Year	Manure N Rate[1]	Fertilizer N Rate	Soil Nitrate	Yield Manure	Yield Manure + FN
		----- kg N ha^{-1} -----		mg NO_3-N kg^{-1}	--------- Mg ha^{-1} ---------	
Winnesheik	01	224	56	10	6.78	7.08
Cherokee	00	264	112	65	8.56	8.60
Chickasaw	00	140	112	22	9.22	9.31
Hancock	00	213	112	17	9.15	9.41
Cherokee	00	335	67	57	9.46	9.43
Buchanan	00	336	56	15	9.58	9.66
Howard	01	286	50	17	9.50	9.74
Franklin	00	280	112	11	9.27	9.80
Hancock	00	213	112	15	10.06	10.04
Howard	01	186	56	20	9.72	10.11
Cerro Gordo	02	217	56	29	10.05	10.15
Hancock	00	213	112	13	9.96	10.15
Hancock	01	152	56	8	10.24	10.18
Boone	01	169	56	11	10.05	10.20
Hancock	01	152	56	7	9.61	10.30
Franklin	01	224	90	14	9.84	10.32
Kossuth	00	168	112	9	10.00	10.40
Hancock	01	152	56	15	10.60	10.50
Greene	02	231	56	12	10.32	10.62
Howard	01	196	50	16	10.50	10.65
Hancock	01	152	56	34	10.65	10.73
Floyd	01	118	56	19	10.66	10.78
Cerro Gordo	02	217	56	27	10.99	10.91
Floyd	00	95	112	27	10.72	10.92
Kossuth	01	232	56	14	10.50	11.12
Kossuth	02	224	56	15	10.63	11.14
Washington	04	-	56	-	10.78	11.18
Greene	00	190	134	26	11.28	11.19
Fayette	01	202	56	-	10.61	11.26
Greene	02	218	56	16	10.98	11.29
Fayette	02	168	57	-	11.37	11.39
Greene	02	209	56	13	11.12	11.44
Cerro Gordo	03	174	56	16	11.50	11.51
Boone	03	168	56	15	11.62	11.82
Cerro Gordo	02	217	56	15	11.67	11.85
Howard	02	139	56	25	11.80	11.90
Cerro Gordo	03	174	56	17	12.03	11.93
Cerro Gordo	03	174	56	23	11.99	11.94
Howard	02	-	56	14	12.04	11.95
Cerro Gordo	02	174	56	0	11.92	12.02
Hardin	03	157	56	-	12.28	12.16
Boone	04	168	56	17	13.54	12.24
Boone	04	168	56	18	12.17	12.59
Greene	04	168	56	20	11.90	12.68
Greene	04	168	56	12	12.35	12.98
Washington	01	-	56	38	13.04	13.24
Buchanan	02	78	73	9	12.40	13.39
Floyd	02	123	56	26	13.59	13.68
Washington	02	-	90	20	13.61	13.81
Greene	03	268	67	19	13.96	14.29
Buchanan	02	202	56	-	14.71	14.52
Mean		196	68	19	11.01	11.19

[1] Rate calculated from analysis of manure sample.

Table 2. Summary of on-farm trials by year and sorted by yield response.

Year	Number of sites	Manure N Rate	Early-spring Rainfall	Yield	
				Manure	Response
		kg N ha^{-1}	mm	---- Mg ha^{-1} ----	
2004	5	174	3429	12.41	0.50
2001	14	203	3099	10.65	0.31
2002	15	200	2311	10.26	0.19
2000	11	174	1702	10.64	0.13
2003	6	180	2311	11.71	0.00

Table 3. Percentage of sites in stalk test categories.

Category[1]	Manure	Manure plus Fertilizer N
	--------------- % ---------------	
low	12	0
marginal	33	26
optimal	33	26
excess	22	48

[1] low, highly probable that additional N would increase yields; marginal, amount of N near optimal; optimal, highly probable that amount of N maximized profits for producers; excess, highly probable amount of N was greater than needed to maximize profits for producers

Table 4. Mean yield response by soil nitrate category.

Soil nitrate	Mean yield response
mg N kg^{-1}	Mg ha^{-1}
< 10	0.52
10 - 30	0.22
> 30	0.05

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CHAPTER VI. GENERAL CONCLUSION

Precision farming technologies enable organized groups of producers to easily evaluate N management practices at many sites and conditions that producers normally encounter during corn production. The methods developed and illustrated in this dissertation document the potential benefits that should be achieved when producers work together to improve N management on their farms. This new system of data collection should help producers improve current (or develop new) recommendations that increase their profits and reduce negative environmental effects associated with N fertilization.